METHODS AND APPARATUS FOR PRE-FILTERING A SIGNAL TO INCREASE SIGNAL-TO-NOISE RATIO AND DECORRELATE NOISE

BACKGROUND OF THE INVENTION

[0001] This invention relates to digital communications apparatus and methods, and more particularly to apparatus and methods for filtering channel taps of a signal in a communication channel.

[0002] Digital communications systems are widely used for voice, image and data communications. When communicating wirelessly, time-varying multipath fading of wireless channels and co-channel interference among wireless channels can make such communication unreliable. Equalization may be used to compensate for the effects of multipath fading and co-channel interference. Some types of equalizers include Maximum Likelihood Sequence Estimation (MLSE), Decision Feedback Equalization (DFE), and Decision Feedback Sequence Estimation (DFSE), reduced-state sequence estimation (RSSE), and an M-algorithm technique.

[0003] Multiple-input-single-output (MISO) and Multiple-input-multiple-output (MIMO) channels arise in many communication applications. A MISO channel may arise when a receiver performs joint detection on co-channel signals using a single antenna. A MIMO channel may arise when a receiver uses antenna diversity, or uses one or multiple antennas for interference rejection, and/or performs multiuser demodulation and/or multicarrier detection.

[0004] Equalization of MIMO channels can be particularly difficult because receiver complexity can grow exponentially with the number of channel impulse response taps (or channel memory) of a received signal. A pre-filter may be used to shape or shorten the channel impulse response taps, which may allow the use of an equalization technique that has a lower complexity than MLSE, such as, for example, DFE, DFSE, RSSE, and the M-algorithm technique.

BRIEF SUMMARY OF THE INVENTION

[0005]   In some embodiments of the present invention, a signal is received from a multiple-input-multiple-output (MIMO) communication channel. Initial channel taps are generated based on an impulse response estimate of the MIMO communication channel. The received signal is pre-filtered using the initial channel taps to generate output channel taps and a corresponding output signal having increased signal to noise ratio (SNR) and uncorrelated noise. The SNR is based on a ratio of the energy in a first subset of the output channel taps to the energy in a second subset of the output channel taps.

[0006]   In some further embodiments of the present invention, the received signal may be pre-filtered to maximize the SNR. The received signal may be pre-filtered so that the second subset of the channel taps includes all channel taps except for the channel taps in the first subset. In some other embodiments of the present invention, the received signal may be pre-filtered so that the second subset of the channel taps includes all channel taps except for the channel taps in the first subset and except for a predetermined number of channel taps that follow the channel taps in the first subset, and which may immediately follow the channel taps in the first subset.

[0007]   In yet some further embodiments of the present invention, some of the channel taps in the first subset may be scaled differently than other channel taps in the first subset. Some of the channel taps in the second subset may be scaled differently than other channel taps in the second subset. Some of the channel taps in the first subset may be scaled differently than some of the channel taps in the second subset.

[0008]   In yet some further embodiments of the present invention, the SNR is based on a ratio of the energy in a first subset of the channel taps to the sum of the energy in the output noise and the energy in a second subset of the channel taps.

[0009]   The output signal may be equalized to provide an estimate of an information sequence in the received signal from the communication channel.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]   Figure 1 is a block diagram of a wireless communication system according to some embodiments of the present invention.

[0011]   Figure 2 illustrates a multiple-input-multiple-output channel model according to some embodiments of the present invention.

[0012]   Figure 3 is a block diagram of a receiver according to some embodiments of the present invention.

[0013]   Figure 4 is a flowchart of operations that may be performed to receive a signal from a communication channel according to some embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0014]   The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. However, this invention should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

[0015]   It also will be understood that, as used herein, the term "comprising" or "comprises" is open-ended, and includes one or more stated elements, steps and/or functions without precluding one or more unstated elements, steps and/or functions.

[0016]   The present invention is described below with reference to block diagrams and/or operational illustrations of methods and wireless terminals according to embodiments of the invention. It is understood that each block of the block diagrams and/or operational illustrations, and combinations of blocks in the block diagrams and/or operational illustrations, can be implemented by radio frequency, analog and/or digital hardware, and/or computer program instructions. These computer program instructions may be provided to a processor of a general purpose computer, special purpose computer, ASIC, and/or other programmable data processing apparatus, such that the instructions, which execute via the processor of the computer and/or other programmable data processing apparatus, create means for implementing the functions/acts specified in the block diagrams and/or operational block or blocks. In some alternate implementations, the functions/acts noted in the blocks may occur out of the order noted in the operational illustrations. For example, two blocks shown in succession may in fact be executed substantially concurrently or the blocks may sometimes be executed in the reverse order, depending upon the functionality/acts involved.

[0017]   As used herein, a "wireless terminal" includes, but is not limited to, a terminal that is configured to communicate via a wireless interface such as, for example, a cellular interface, a wireless local area network interface (WLAN), Bluetooth interface, another RF communication interface, and/or an optical interface. Example wireless terminals include, but are not limited to, a cellular wireless terminal; a personal communication terminal that may combine a cellular wireless terminal with data processing, facsimile and

data communications capabilities; a personal data assistance (PDA) that can include a wireless transceiver, pager, Internet/intranet access, local area network interface, wide area network interface, Web browser, organizer, and/or calendar; and a mobile or fixed computer or other device that includes a wireless transceiver. The wireless terminal may be configured to communicate via a cellular communication link that may include a protocol such as, for example, ANSI-136, Global Standard for Mobile (GSM) communication, General Packet Radio Service (GPRS), enhanced data rates for GSM evolution (EDGE), code division multiple access (CDMA), wideband-CDMA, CDMA2000, and UMTS. Communication protocols as used herein may specify the information communicated, the timing, the frequency, the modulation, and/or the operations for setting-up and/or maintaining a communication connection.

[0018]   Figure 1 is a functional block diagram of an exemplary wireless communication system that includes a plurality of base stations 102 and 104 that are connected to one or more mobile services switching centers (MSC) 106. Each of the base stations 102 and 104 are located in, and provide services to, a geographic region referred to as a cell, 108 and 110, respectively. In general, there is one base station for each cell. Within each cell, there may be a plurality of wireless terminals 100 that communicate via radio link with a base station that services the cell in a manner well known in the art. The base stations 102 and 104 allow a user of the wireless terminal 100 to communicate with other wireless terminals 100, or with users connected to a Public Switched Telephone Network (PSTN) 112. The MSC 106 routes calls to and from the wireless terminal 100 through one of the base stations 102 and 104 that, for example, provides the strongest communication link to the wireless terminal 100. Information concerning the cell location and activity status of the wireless terminal 100 is stored in a Home Location Register (not shown) and a Visitor Location Register (not shown), which may be incorporated into, or otherwise communicate with, the MSC 106. Although only two cells 108 and 110 are shown for illustration purposes, a typical cellular communications system may include hundreds of cells and may service thousands of wireless terminals 100.

[0019]   The wireless terminal 100 includes a processor 132, a transceiver 134, a memory 136 and may also include a speaker 140, a microphone 142, a display 144, and a keypad 146. The memory 136 may include one or more erasable programmable read-only memories (EPROM or Flash EPROM), battery backed random access memory (RAM), magnetic, optical, or other digital storage device, and may be separate from, or at least partially within, the processor 132. The processor 132 may include more than one processing

component, such as, for example, a general purpose processor and a digital signal processor, which may be enclosed in a common package or separate and apart from one another. The transceiver 134 typically includes both a transmitter 148 and a receiver 150 to allow two way communications, but the present invention is not limited to such devices and, as used herein, a "transceiver" may include only the receiver 150. The wireless terminal 100 may communicate with the base stations 102 and 104 using radio frequency signals, which may be communicated through an antenna 152 over one or more communication channels according to one or more cellular communication protocols.

[0020]   Figure 3 is a block diagram of a receiver 300 according to various embodiments of the present invention. The receiver 300 may be used, for example, as receiver 150 in Figure 1. An antenna 310 is configured to receive an incident signal from a MIMO communication channel. An RF front end 320 downconverts the received signal to a baseband frequency and amplifies the downconverted signal. The signal is then converted to a digital signal by an analog-to-digital converter 330 and downsampled to a lower data rate by a digital sampler 340. A channel estimator 345 generates channel taps based on an impulse response estimate of the digital signal from the digital sampler 340. A pre-filter 350 pre-filters the received signal to generate an output signal having increased signal-to-noise ratio (SNR) and uncorrelated noise. The SNR is based on a ratio of energy in a first subset of the output channel taps to energy in a second subset of the output channel taps. The pre-filter 350 may pre-filter the received signal to maximize the SNR at the output .

[0021]   The pre-filter 350 may pre-filter the received signal based on Channel Shortening Equalization (CSE) filtering in which it pre-filters the received signal with the second subset of the channel taps including all channel taps except for the first subset of the channel taps. The pre-filter 350 may alternatively pre-filter the channel taps based on Decision Feedback Equalization (DFE) filtering in which it pre-filters the received signal with the second subset of the channel taps including all channel taps except for the first subset of the channel taps and except for a predetermined number of channel taps following, or immediately following, the first subset of the channel taps.

[0022]   An equalizer 360 equalizes the output signal to provide an estimate of an information sequence in the received signal from the MIMO communication channel.

[0023]   In some embodiments of the present invention, the pre-filter 350 is a FIR pre-filter that maximizes the SNR for MIMO systems. The SNR may be a sum of output branch SNRs under the condition that the branch noises are uncorrelated. The SNR may be based on event error analysis of MIMO systems. The pre-filter 350 may be a maximum-SNR

5

(Max-SNR) class of pre-filters that includes CSE and DFE pre-filters, and which are referred to herein as Max-SNR-CSE and Max-SNR-DFE pre-filters, respectively. Moreover, some embodiments of the pre-filter 350 are configured as a hybrid pre-filter. A Max-SNR-DFE pre-filter may differ from a MMSE-DFE pre-filter in that the Max-SNR-DFE pre-filter maximizes the SNR, while the MMSE-DFE pre-filter minimizes the error (or noise) while constraining the signal to be an identity matrix. The hybrid Max-SNR-CSE pre-filter differs from the Max-SNR-CSE pre-filter in that the suppression of the feedback taps is relaxed in the hybrid pre-filter. Some embodiments of the pre-filter 350 allow the input channel responses to be delayed with respect to each other to match their channel phase characteristics.

[0024]   The communication channel and receiver 300 may be mathematically modeled as described below. For purposes of illustration only, the communication channel and receiver 300 are assumed to have n_i inputs and n_o outputs that are affected by inter-symbol interference (ISI) and additive zero-mean noise. Figure 2 shows such a communication channel having n_i transmitting antennas and n_o receiving antennas, and where $x_k^{(i)}, y_k^{(j)}, w_k^{(j)}$ and $h_m^{(i,j)}$ are the ith channel input, the jth channel output, the noise affecting the jth output and the mth channel tap between the ith input and the jth output at time k, respectively. The complex-valued baseband signal may be modeled as

$$\underline{y}_k = \sum_{m=0}^{L} H_m \underline{x}_{k-m} + \underline{w}_k \ , \tag{1}$$

where $\underline{y}_k = \left[y_k^{(1)}, y_k^{(2)}, ..., y_k^{(n_o)} \right]^T, \underline{x}_k = \left[x_k^{(1)}, x_k^{(2)}, ..., x_k^{(n_i)} \right]^T$ and

$\underline{w}_k = \left[w_k^{(1)}, w_k^{(2)}, ..., w_k^{(n_o)} \right]^T$ are the channel output vector, the channel input vector, and the noise vector for time k, respectively, and H_m is the n_o x n_i matrix channel tap where L is the channel memory. By stacking M samples of the output vector, the system model may be equivalently written as Equation 2 below,

$$\begin{bmatrix} \underline{y}_{k+M-1} \\ \underline{y}_{k+M-2} \\ \vdots \\ \underline{y}_k \end{bmatrix} + \begin{bmatrix} H_0 & H_1 & \cdots & H_L & 0 & \cdots & 0 \\ 0 & H_0 & H_1 & \cdots & H_L & \ddots & \vdots \\ \vdots & \ddots & & & & & 0 \\ 0 & \cdots & 0 & H_0 & H_1 & \cdots & H_L \end{bmatrix} \begin{bmatrix} \underline{x}_{k+M-1} \\ \underline{x}_{k+M-2} \\ \vdots \\ \underline{x}_{k-L} \end{bmatrix} + \begin{bmatrix} \underline{w}_{k+M-1} \\ \underline{w}_{k+M-2} \\ \vdots \\ \underline{w}_k \end{bmatrix}, \tag{2}$$

or which may be more compactly written as Equation 3,

$$\underline{y} = H\underline{x} + \underline{w} ,$$ (3)

where the matrix H is $n_o M \times n_i (L + M)$.

[0025]   For purposes of illustration only, the pre-filter 350 may be modeled as follows. Let $F = \left[F_0^H, F_1^H, \ldots, F_{M-1}^H\right]^H$ be a MIMO pre-filter with M matrix taps of size $n_o \times n_o$ each. The $n_o \times 1$ filtered signal vector $\underline{y}'$ is provided by

$$y' = F^H \underline{y} = F^H H \underline{x} + F^H \underline{w}.$$ (4)

Note that the $n_i(L+M)$ columns of the matrix $F^H H$ represent $L + M$ taps of the filtered channel response. The filtered channel taps are divided into two groups: "desired channel taps $F^H H \Delta_d$" and "undesired channel taps $F^H H \Delta_u$", where Δ_d and Δ_u are diagonal matrices that select the columns of the matrix H corresponding to the desired and undesired channel taps, respectively. By selecting appropriate matrices Δ_d and Δ_u, the filter can be designed for channel shortening equalization (CSE), decision feedback equalization (DFE) or a combination thereof (hybrid). This will be discussed in detail further below. However, the design problem is first described as follows.

[0026]   The filtered signal corresponding to the desired channel taps, given by $F^H H \Delta_d \underline{x}$, is referred to as the "filtered desired signal". The sum of the undesired signal and noise after pre-filtering, given by $\underline{z} = F^H \Delta_u \underline{x} + F^H \underline{w}$, is referred to as the "filtered noise". In some embodiments of the present invention, the energy in the filtered desired signal is maximized relative to the energy in the filtered noise. It is assumed that the input and noise are mutually uncorrelated and have autocorrelation matrices $R_x = E\left[\underline{x}\underline{x}^H\right]$ and $R_w = E\left[\underline{w}\underline{w}^H\right]$, respectively. The autorcorrelation of the filtered desired signal is then given by $F^H B F$, where $B = H\Delta_d R_x \Delta_d^H H^H$ is the autocorrelation of the input desired signal. The autocorrelation of the filtered noise is provided by

$$E\left[\underline{z}\underline{z}^H\right] = F^H A F ,$$ (5)

where $A = H\Delta_u R_x \Delta_u^H H^H + R_w$ is the autocorrelation of the total noise (undesired signal plus noise). The filtered noise has zero mean if the input $\underline{x}$ has zero mean. Note that the filtered desired signal and noise power for the nth output branch is given by $\underline{f}_n^H B \underline{f}_n$ and $\underline{f}_n^H A \underline{f}_n$.

7

respectively, where $\underline{f}_n$ (the nth column of the matrix F) is the pre-filter for the nth output branch.

[0027] Assuming that the filtered noise affecting the output branches is independent, i.e.,

$$\underline{f}_n^H A \underline{f}_m = 0 \forall m \neq n \ . \tag{6}$$

The SNR is then

$$SNR = \sum_{n=1}^{n_o} SNR_n \ , \tag{7}$$

where SNR_n is the signal-to-noise ratio for the nth output branch, provided by

$$SNR_n = \frac{\underline{f}_n^H B \underline{f}_n}{\underline{f}_n^H A \underline{f}_n} \ . \tag{8}$$

The pre-filter may be configured to maximize the SNR as provided by Equation 7.

[0028] Assuming that the total noise autocorrelatin matrix A is positive definite, such as in the presence of ambient or thermal noise, the matrix A can be decomposed as:

$$A = U\Gamma^2 U^H \ , \tag{9}$$

where Γ^2 is a diagonal matrix containing the eigen-values of the matrix A which are all positive and the matrix U is unitary. Letting $P = \Gamma U^H F$ the SNR is given by

$$SNR = \sum_{n=1}^{n_o} \frac{\underline{p}_n^H C \underline{p}_n}{\underline{p}_n^H \underline{p}_n} \ , \tag{10}$$

where $\underline{p}_n$ is the nth column of the matrix P and $C = \Gamma^{-1} U^H B U \Gamma^{-1}$. Assuming that the vector $\underline{p}_n$ has unit power for all n, the SNR is provided by

$$SNR = \sum_{n=1}^{n_o} \underline{p}_n^H C \underline{p}_n \ . \tag{11}$$

The SNR may be maximized under the condition

$$\underline{p}_n^H \underline{p}_m = \begin{cases} 1 & n=m \\ 0 & n \neq m \end{cases} \ . \tag{12}$$

which follows from Equation 6. Note that the matrix C is positive semi-definite. Therefore, it can be decomposed as $C = V\Lambda^2 V^H$, where the matrix Λ^2 is a diagonal matrix comprising non-negative eigen-values λ_n^2 of the matrix C and the matrix V is unitary.

[0029]   The maximum SNR that is obtained by Equation 12 is provided by

$$\text{SNR} = \sum_{n=1}^{n_o} \lambda_n^2 \quad , \tag{13}$$

where λ_n^2 are the n_o largest eigen-values of the matrix C. The filters $F^{opt} = \left[\underline{f}_1^{opt}, \underline{f}_2^{opt}, ..., \underline{f}_{n_o}^{opt} \right]$ that achieve the maximum SNR are given by an orthonormal linear combination of the vectors $U\Gamma^{-1}\left[\underline{v}_1, \underline{v}_2, ..., \underline{v}_{n_0} \right]$, where $\underline{v}_1, \underline{v}_2, ..., \underline{v}_{n_o}$ are the eigen-vectors corresponding to the n_o largest eigen-values of the matrix C.

[0030]   A Max-SNR pre-filter may be configured as described below. By selecting the diagonal matrices Δ_d and Δ_u appropriately, the pre-filter 350 can be designed for channel shortening equalization (CSE), decision feedback equalization (DFE) or a combination thereof (hybrid). The pre-filter 350 may be configured with delay δ, n_m main taps and n_b feedback taps, by the following diagonal matrices:

$$\Delta_d = \text{diag}\left(O_{n_i\delta}, I_{n_i n_m}. O_{n_i(L+M-\delta-n_m)} \right) \quad , \text{ and} \tag{14}$$

$$\Delta_u = \text{diag}\left(I_{n_i\delta}. O_{n_i n_m}. \gamma I_{n\, n_b}. I_{n_i(L+M-\delta-n_m-n_b)} \right) , \tag{15}$$

where I_n and O_n are identity and zero matrices of dimension $n \times n$, respectively, and γ is a scalar design variable referred to as the scaling factor. A CSE pre-filter is obtained by selecting $\gamma = 1$ and $n_b = 0$. A DFE pre-filter is obtained by selecting $\gamma = 0$ and $n_m = 1$. Note that the CSE pre-filter is designed to maximize the ratio of the energy in the main channel taps to the energy in the rest of the taps, while the DFE pre-filter is designed to maximize the ratio of the energy in one channel tap to the energy in the rest of the taps except the feedback taps. The feedback taps may be either completely supressed in CSE, or not suppressed at all in DFE. For a practical DFSE receiver, it may be desirable to find middle ground in choosing the feedback taps, because the feedback taps contribute to the signal energy captured while they also contribute to error propagation if they are too large. The feedback taps can be scaled up or down by setting the scaling factor γ to be between 0 and 1. A CSE pre-filter with $\gamma < 1$ is

referred to herein as a hybrid CSE pre-filter, and similarly a DFE pre-filter with $\gamma > 0$ is referred to herein as a hybrid DFE pre-filter.

[0031] It may be apparent to those skilled in the art in view of the present invention that the feedback taps may be used as part of the desired taps in the matrix Δ_d, and may be scaled down with respect to the main taps. Moreover, each feedback tap may be scaled separately and/or differently. The desired taps may be scaled differently based on different input channels (which may corresond to different users).

[0032] The Max-SNR CSE approach, described above, may maximize the energy in the main channel taps while constraining the noise to have an identity autocorrelation matrix. The hybrid Max-SNR-CSE pre-filter described above may provide a better SNR than the Max-SNR-CSE pre-filter because the feedback taps are not suppressed completely. The hybrid approach may thereby be more suitable for receivers that use DFE.

[0033] It may be apparent to those skilled in the art in view of the present invention that the pre-filters described above can be optimized for the filter delay δ . The optimization may be done on the basis of the SNR as defined by Equation 7, and/or may use an alternative SNR definition which takes into account the signal energy contained in the feedback channel taps.

[0034] The delay for each input branch may be optimized, or the relative delay can be optimized for a chosen filter delay. Such optimization may also be performed on the basis of the SNR as defined in Equation 7, or by another SNR definition.

[0035] Figure 4 illustrates a flow-chart of some of the primary operations that may be performed by a receiver according to some embodiments of the present invention. At Block 400, channel taps are generated based on an impulse response estimate of a MIMO communication channel. At Block 410, a received signal is pre-filtered to generate an output signal having increased SNR and uncorrelated noise. The SNR is based on a ratio of the energy in a first subset of the output channel taps to the energy in a second subset of the output channel taps. At Block 420, the output signal is equalized to provide an estimate of an information sequence in the received signal.

[0036] In the drawings and specification, there have been disclosed embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.